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## The darkest shadows: deep mid-infrared extinction mapping of a massive protocluster

Butler, Michael J ; Tan, Jonathan C ; Kainulainen, Jouni

**Abstract:** We use deep 8  $\mu$ m Spitzer-IRAC imaging of massive Infrared Dark Cloud (IRDC) G028.37+00.07 to construct a mid-infrared (MIR) extinction map that probes mass surface densities up to  $\Sigma = 1 \text{ g cm}^{-2}$  ( $A_V = 200 \text{ mag}$ ), amongst the highest values yet probed by extinction mapping. Merging with an NIR extinction map of the region creates a high dynamic range map that reveals structures down to  $A_V = 1 \text{ mag}$ . We utilize the map to: (1) measure a cloud mass  $7 \times 10^4 M_\odot$  within a radius of 8 pc. 13CO kinematics indicate that the cloud is gravitationally bound. It thus has the potential to form one of the most massive young star clusters known in the Galaxy. (2) Characterize the structures of 16 massive cores within the IRDC, finding they can be fit by singular polytropic spheres with  $\rho \propto r^{-k_\rho}$  and  $k = 1.3 \pm 0.3$ . They have  $\bar{\Sigma} \simeq 0.1 - 0.4 \text{ g cm}^{-2}$  relatively low values that, along with their measured cold temperatures, suggest that magnetic fields, rather than radiative heating, are important for controlling fragmentation of these cores. (3) Determine the (equivalently column density) PDF is well fit by a single log-normal with mean  $\bar{A}_V \simeq 9 \text{ mag}$ , high compared to other known clouds. It does not exhibit a power law tail, which has been claimed to indicate the importance of self-gravity. However, we suggest that the PDF does not, self-gravitating hierarchy of structures present over a wider range of scales in the cloud.

DOI: <https://doi.org/10.1088/2041-8205/782/2/L30>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-98795>

Journal Article

Published Version

Originally published at:

Butler, Michael J; Tan, Jonathan C; Kainulainen, Jouni (2014). The darkest shadows: deep mid-infrared extinction mapping of a massive protocluster. *Astrophysical Journal Letters*, 782(2):L30.

DOI: <https://doi.org/10.1088/2041-8205/782/2/L30>

## THE DARKEST SHADOWS: DEEP MID-INFRARED EXTINCTION MAPPING OF A MASSIVE PROTOCLUSTER

MICHAEL J. BUTLER<sup>1</sup>, JONATHAN C. TAN<sup>2</sup>, AND JOUNI KAINULAINEN<sup>3</sup>

<sup>1</sup> Institute of Theoretical Physics, University of Zürich, CH-8057 Zürich, Switzerland

<sup>2</sup> Departments of Astronomy & Physics, University of Florida, Gainesville, FL 32611, USA

<sup>3</sup> Max-Planck-Institute for Astronomy, Königstuhl 17, D-69117, Heidelberg, Germany

Received 2013 November 4; accepted 2014 January 20; published 2014 February 5

### ABSTRACT

We use deep  $8\,\mu\text{m}$  *Spitzer*-IRAC imaging of massive Infrared Dark Cloud (IRDC) G028.37+00.07 to construct a mid-infrared (MIR) extinction map that probes mass surface densities up to  $\Sigma \sim 1\,\text{g cm}^{-2}$  ( $A_V \sim 200\,\text{mag}$ ), amongst the highest values yet probed by extinction mapping. Merging with an NIR extinction map of the region creates a high dynamic range map that reveals structures down to  $A_V \sim 1\,\text{mag}$ . We utilize the map to: (1) measure a cloud mass  $\sim 7 \times 10^4 M_\odot$  within a radius of  $\sim 8\,\text{pc}$ .  $^{13}\text{CO}$  kinematics indicate that the cloud is gravitationally bound. It thus has the potential to form one of the most massive young star clusters known in the Galaxy. (2) Characterize the structures of 16 massive cores within the IRDC, finding they can be fit by singular polytropic spheres with  $\rho \propto r^{-k_\rho}$  and  $k_\rho = 1.3 \pm 0.3$ . They have  $\bar{\Sigma} \simeq 0.1\text{--}0.4\,\text{g cm}^{-2}$ —relatively low values that, along with their measured cold temperatures, suggest that magnetic fields, rather than accretion-powered radiative heating, are important for controlling fragmentation of these cores. (3) Determine the  $\Sigma$  (equivalently column density or  $A_V$ ) probability distribution function (PDF) for a region that is nearly complete for  $A_V > 3\,\text{mag}$ . The PDF is well fit by a single log-normal with mean  $\bar{A}_V \simeq 9\,\text{mag}$ , high compared to other known clouds. It does not exhibit a separate high-end power law tail, which has been claimed to indicate the importance of self-gravity. However, we suggest that the PDF does result from a self-similar, self-gravitating hierarchy of structures present over a wide range of scales in the cloud.

**Key words:** dust, extinction – ISM: clouds – stars: formation

**Online-only material:** color figures

### 1. INTRODUCTION

Most stars, especially massive ones, form in clusters from dense clumps of gas inside giant molecular clouds (e.g., McKee & Ostriker 2007). Turbulence and magnetic fields are thought to help regulate star formation activity, but both their absolute and relative importance are uncertain. These can affect the overall timescale of star cluster formation, be it dynamically fast (Elmegreen 2007) or slow (Tan et al. 2006), the fragmentation of the gas into self-gravitating cores (Padoan & Nordlund 2002; Vázquez-Semadeni et al. 2005; Kunz & Mouschovias 2009), and thus the mechanism by which massive stars are born, i.e., via competitive clump-fed accretion (Bonnell et al. 2001; Wang et al. 2010) or via core accretion (McKee & Tan 2003), and the stellar initial mass function established.

Progress requires improved observational constraints on the properties of dense gas clumps that are on the verge of massive star and star cluster formation, such as the cold, high column density clouds that reveal themselves as Infrared Dark Clouds (IRDCs), silhouetted against the MIR emission from the Galactic diffuse interstellar medium (ISM; e.g., Carey et al. 1998; Rathborne et al. 2006; Butler & Tan 2009). IRDCs suffer from CO freeze out onto dust grains (e.g., Hernandez et al. 2011) and thus have typically been studied via their millimeter to far-IR (FIR) dust continuum emission (e.g., Rathborne et al. 2006; Peretto et al. 2010). This method has the disadvantage of requiring knowledge of both the emissivity and temperature of dust in the cloud. Single dish observations are needed to recover the total flux, but these have relatively poor angular resolution (e.g.,  $11''$  FWHM angular resolution for the 1.2 mm observations of Rathborne et al. 2006 with the IRAM 30 m

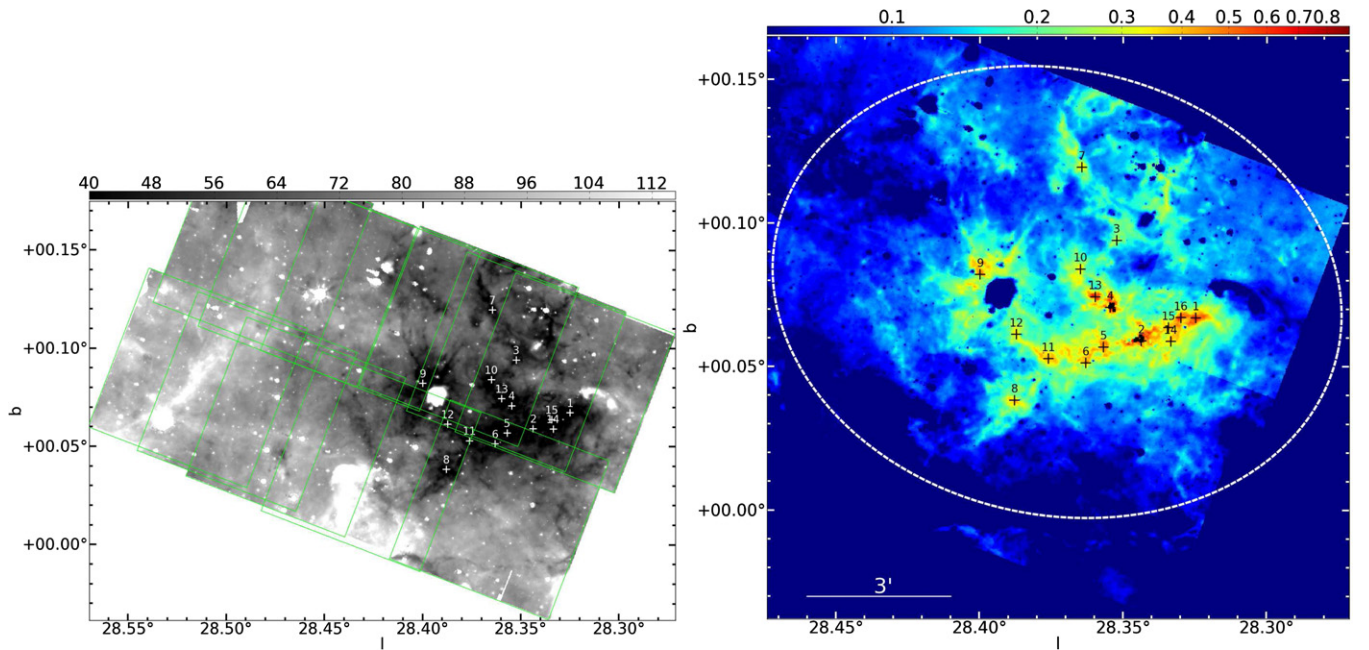
telescope;  $\sim 22''$  for the  $250\,\mu\text{m}$  observations of Peretto et al. 2010 with *Herschel*-SPIRE). Interferometric observations are possible at submillimeter and longer wavelengths, but on their own provide poor constraints on dust temperature.

Extinction mapping is a temperature-independent method to probe cloud structure. However, using background stars in the NIR, clouds are typically only probed up to  $A_V \simeq 25\,\text{mag}$ <sup>4</sup> (Kainulainen et al. 2011), while IRDCs can have column densities  $\sim 10\times$  larger. Furthermore, the location of IRDCs at  $\gtrsim \text{kpc}$  distances in the crowded Galactic plane, with NIR sources at a range of distances, necessitates statistical methods that limit the effective angular resolution of the maps to  $\sim 30''$ .

Thus, MIR extinction (MIREX) mapping has proven more effective at probing IRDCs, e.g., with  $2''$  angular resolution achieved with *Spitzer*-IRAC GLIMPSE (Churchwell et al. 2009)  $8\,\mu\text{m}$  images (e.g., Butler & Tan 2009). Using the foreground estimation method of Butler & Tan (2012), the maximum  $\Sigma$  that can be probed depends on the noise level of the images: a  $1\sigma$  level of  $0.6\,\text{MJy sr}^{-1}$  for GLIMPSE images leads to a maximum, “saturation,” mass surface density of  $\Sigma_{\text{sat}} \sim 0.3\text{--}0.5\,\text{g cm}^{-2}$  for typical inner Galaxy IRDCs. Since it compares specific intensities toward the IRDC with those of its surroundings, MIREX mapping has difficulties at lower  $\Sigma$  values, where it tends to underestimate true extinctions by  $A_V \sim 5\text{--}10\,\text{mag}$ . This deficiency can be fixed by combining MIR and NIR-derived maps (Kainulainen & Tan 2013).

Here we present an  $8\,\mu\text{m}$  extinction map of IRDC G028.37+00.07, hereafter IRDC C (Butler & Tan 2009), with

<sup>4</sup> We interchange between  $\Sigma$ ,  $N_{\text{H}}$  and  $A_V$  via  $A_V/(1\,\text{mag}) \equiv N_{\text{H}}/(1.9 \times 10^{21}\,\text{cm}^{-2}) \equiv \Sigma/(4.45 \times 10^{-3}\,\text{g cm}^{-2})$  (see Kainulainen & Tan 2013).



**Figure 1.** (a) Left:  $8\ \mu\text{m}$  image of IRDC G028.37+00.07 (Cloud C) with intensity scale in  $\text{MJy sr}^{-1}$ . Dotted squares show the 12 *Spitzer* IRAC pointings, each with 10.4 s exposure, used to construct the mosaicked image. (b) Right: merged NIR+MIR  $\Sigma$  map (units of  $\text{g cm}^{-2}$ ). The IRDC-defining ellipse from Simon et al. (2006) is shown. Core/clump centers (Section 3.2) are labeled with crosses. Saturated pixels are marked with white squares.

(A color version of this figure is available in the online journal.)

kinematic distance of 5.0 kpc (Simon et al. 2006) made using longer-exposure archival *Spitzer*-IRAC data, probing to  $\Sigma_{\text{sat}} \simeq 1\ \text{g cm}^{-2}$ . Combining with an NIR extinction map, it reveals a very high dynamic range of mass surface densities.

## 2. METHODS

Butler & Tan (2012) MIREX mapping requires knowing the intensity of radiation just behind the cloud,  $I_{\nu,0}$  (estimated by interpolation of surrounding observed intensities), and just in front,  $I_{\nu,1}$ . Then for negligible emission in the cloud and a one-dimensional geometry,  $I_{\nu,1} = e^{-\tau_\nu} I_{\nu,0}$ , where optical depth  $\tau_\nu = \kappa_\nu \Sigma$ , where  $\kappa_\nu$  is total opacity at frequency  $\nu$  per unit total mass. However, foreground emission from the diffuse ISM emission causes us to observe  $I_{\nu,1,\text{obs}} = I_{\nu,\text{fore}} + I_{\nu,1} = I_{\nu,\text{fore}} + e^{-\tau_\nu} I_{\nu,0}$  toward the IRDC and  $I_{\nu,0,\text{obs}} = I_{\nu,\text{fore}} + I_{\nu,0}$  toward the surroundings used to estimate  $I_{\nu,0}$ .

Following Butler & Tan (2012), we estimate  $I_{\nu,\text{fore}}$  by searching for saturation in independent cores, occurring when  $\Sigma$  is large enough to block essentially all background emission. Butler & Tan (2012) used *Spitzer* GLIMPSE data with 2.4 s exposures. We now use archival data of IRDC C (PI: G. Fazio; Project ID DARKCLOUDS/219; AOR key 6050304), with 10.4 s exposure per pointing. After starting with post basic calibrated data (pipeline version S18.18.0), the final combined image consists of 12 mosaicked  $5.2 \times 5.2$  pointings, resulting in  $\sim 20$  regions that have different total exposures,  $1\sigma$  noise and instrumental background levels (Figure 1(a)). For each region with area  $\gtrsim 500$  pixels, we search for saturation by: (1) find  $I_{\nu,1,\text{obs}}(\text{min})$ , the minimum value of  $I_{\nu,1,\text{obs}}$ . (2) Find all pixels with  $I_{\nu,1,\text{obs}}(\text{min}) < I_{\nu,1,\text{obs}} < I_{\nu,1,\text{obs}}(\text{min}) + 2\sigma$ . If these are spatially independent (i.e., extended over  $\gtrsim 4''$ ; cf.  $8''$  of Butler & Tan 2012), then the region is defined to exhibit “local saturation” and all pixels in this intensity range are labeled “saturated.” Steps (1) and (2) are repeated for each region. (3) Evaluate the mean value of  $I_{\nu,1,\text{obs}}$  of saturated pixels in all regions,  $I_{\nu,1,\text{obs}}(\text{sat})$  (in

practice only two regions exhibit saturation; see Section 3.2). Apply an offset to each saturated region equal to the difference between  $I_{\nu,1,\text{obs}}(\text{sat})$  and its local value. We expect these offsets to result from varying instrumental background noise. We then subtract a local  $2\sigma$  intensity from the foreground to each region, which ensures every pixel has a finite estimate of  $\Sigma$ . The average estimate of  $I_{\nu,\text{fore}}$  is  $\simeq 31.2\ \text{MJy sr}^{-1}$  ( $\simeq 0.6\ \text{MJy sr}^{-1}$  greater than the Butler & Tan 2012 value). Lack of areal coverage of the archival data means we must use the background model derived from GLIMPSE (Butler & Tan 2012). This was scaled to match intensities of the archival data by comparing median intensities in several small patches free of stellar or extended emission sources, which were used to derive a single mean offset factor.

Longer integration times (everywhere  $\geq 10.4$  s; all identified core/clumps (Section 3.2) have  $\geq 20.8$  s, up to maximum of 52 s; compared to 2.4 s for GLIMPSE) cause the  $1\sigma$  noise level to fall from  $\sim 0.6\ \text{MJy sr}^{-1}$  (Reach et al. 2006) to 0.29, 0.20, and  $0.14\ \text{MJy sr}^{-1}$  for the 10.4, 20.8, and 41.6 s exposure regions, respectively. While the absolute value of this noise level is somewhat uncertain, the relative values should be better determined. By subtracting a  $2\sigma$  noise level, our method sets the minimum value of  $I_{\nu,1} \simeq 1\sigma - 2\sigma$ , leading to a limit at which our  $\Sigma$  measurements begin to be underestimated by saturation effects,  $\Sigma_{\text{sat}} = \tau_{\nu,\text{sat}}/\kappa_\nu = \ln(I_{\nu,0}/I_{\nu,1})/\kappa_\nu$ , of 0.625, 0.675,  $0.722\ \text{g cm}^{-2}$  respectively, assuming  $I_{\nu,1} = 2\sigma$  and a value of  $I_{\nu,0} = I_{\nu,0,\text{obs}} - I_{\nu,\text{fore}} = (94.3 - 31.2 = 63.1)\ \text{MJy sr}^{-1}$ , the mean intensity of our scaled background model with foreground subtracted. This represents an increase of up to  $\sim 40\%$  in dynamic range compared to the Butler & Tan (2012) map, which had  $\Sigma_{\text{sat}} \simeq 0.5\ \text{g cm}^{-2}$ . A true  $\Sigma$  value that is equal to  $\Sigma_{\text{sat}}$  is underestimated by about 7% (cf. 17% for Butler & Tan 2012). Thus the new map not only probes to higher  $\Sigma$ , but does so with greater accuracy. Note, values of  $\Sigma > \Sigma_{\text{sat}}$  are present in the map, up to  $\sim 0.85\ \text{g cm}^{-2}$ .

The above equation for  $\Sigma_{\text{sat}}$  is also useful for seeing the effect of errors in estimating the background specific intensity,



$I_{v,0}$ . This is expected to show fluctuations about the median interpolated level: Butler & Tan (2009) find the HWHM of the distribution of background intensities around IRDC C to be a factor of 1.2. This introduces an error of  $\Delta\Sigma = (\ln 1.2)/\kappa_v \rightarrow 0.024 \text{ g cm}^{-2}$ , which is only a  $\sim 3\%$ – $4\%$  error for  $\Sigma \simeq \Sigma_{\text{sat}}$ , growing to 20% in the optically thin limit.

In several locations,  $\Sigma$  “holes” are seen, where  $\Sigma$  is significantly lower than the surrounding pixels. This could be caused by the presence of a real MIR-bright point source or by an instrumental artifact, such as a bad pixel. To identify the latter, we use the original GLIMPSE  $8 \mu\text{m}$  image as a reference. If there is no source in the GLIMPSE image, then the hole in the new image is corrected by replacing the bad pixel with the mean of the nearest unaffected pixels. This typically occurs far from any of the centers of our core sample (Section 3.2), with the exception of C1, which had a hole directly adjacent to core center.

Finally, we follow Kainulainen & Tan (2013) to merge the MIREX map with an NIR extinction map of the region, derived using the method of Kainulainen et al. (2011) and data from the *UKIRT/Galactic Plane Survey* (Lawrence et al. 2007). The technique estimates NIR extinction toward background stars by comparing their NIR colors to those of stars in a nearby reference field. The zero-point calibration uncertainty is estimated to be  $A_V \sim 1 \text{ mag}$ . To combine the NIR and MIR extinction maps, a relative dust opacity-law of  $\tau_{8\mu\text{m}} = 0.29\tau_K$  is adopted (Kainulainen & Tan 2013). The net effect of the combination is a zero point shift of the MIREX map by  $A_V \sim 5$ – $10 \text{ mag}$ , which varies at the resolution of the NIR map of  $30''$ . In regions where  $A_V \gtrsim 15 \text{ mag}$ , the NIR map is not accurate so we interpolate its value from surrounding regions. The final combined map is shown in Figure 1(b).

### 3. RESULTS

#### 3.1. Overall Cloud Mass and Dynamics

Inside the IRDC elliptical boundary of Simon et al. (2006; effective radius of  $R_{\text{eff}} = 7.7 \text{ pc}$ ,  $e = 0.632$ ) the mean mass surface density is  $\bar{\Sigma} = 0.0926 \text{ g cm}^{-2}$  (ignoring regions affected by MIR-bright sources). We assume a 30% uncertainty due to the opacity per unit mass, which includes dust opacity and dust-to-gas mass ratio uncertainties (Butler & Tan 2012). This result is 28% higher than the value of  $\bar{\Sigma} = 0.0721 \text{ g cm}^{-2}$  from (Kainulainen & Tan 2013), which we attribute to the new map’s ability to probe to higher values of  $\Sigma$ .

Given  $\bar{\Sigma}$  and the kinematic distance of  $5.0 \text{ kpc}$ , for which we assume 20% uncertainty, the total IRDC mass inside the ellipse is  $M = 6.83 \times 10^4 M_\odot$ , with 50% overall uncertainty. This compares with our previous estimate of  $5.32 \times 10^4 M_\odot$  (Kainulainen & Tan 2013). This shows that IRDC C is one of the more massive molecular clumps in the Galaxy. Its mass is comparable to the  $1.1 \text{ mm}$  Bolocam Galactic Plane Survey clumps of Ginsburg et al. (2012) and the  $1.3 \times 10^5 M_\odot$ ,  $2.8 \text{ pc}$  radius Galactic center clump (the “Brick”) of Longmore et al. (2012). Note that these masses are based on dust continuum emission and thus suffer from additional uncertainties due to dust temperature estimates. With this caveat in mind, these massive millimeter clumps appear to be a factor of about 10 denser than IRDC C, which, inside  $R_{\text{eff}}$ , we estimate to be  $n_{\text{H}} \simeq 1120 \text{ cm}^{-3}$  (but with the caveat of assuming spherical geometry), corresponding to a free-fall time of  $t_{\text{ff}} = [3\pi/(32G\rho)]^{1/2} = 1.30 \times 10^6 \text{ yr}$ . Apart from the Brick, the millimeter clumps are typically already undergoing active star formation. Some stars have started to form in IRDC C (e.g., the

MIR-bright sources; see also Zhang et al. 2009), but overall the star formation activity appears to be relatively low, and so this cloud should represent an earlier stage of massive star cluster formation.

From  $^{13}\text{CO}(1-0)$  Galactic Ring Survey data (Jackson et al. 2006), the IRDC’s one-dimensional velocity dispersion,  $\sigma$  (integrating over the Simon et al. (2006) ellipse), is  $3.41$ – $3.75 \text{ km s}^{-1}$  (depending on method of Gaussian fitting or total integration; Kainulainen & Tan 2013). If the cloud is virialized, then  $\sigma$  should be  $4.2 \text{ km s}^{-1}$  (ignoring surface pressure and magnetic field terms and evaluated for a spherical cloud with internal power law density profile of  $\rho \propto r^{-k_{\rho,\text{cl}}}$  with  $k_{\rho,\text{cl}} = 1$ ; Bertoldi & McKee 1992). Support by large scale magnetic fields would reduce the virial equilibrium velocity dispersion, although such support is unlikely to be dominant given an expected field strength of  $12 \mu\text{G}$  implied by the cloud’s mean density (Crutcher et al. 2010). Thus, overall the cloud appears close to virial equilibrium (or perhaps sub-virial), implying it is gravitationally bound and that self-gravity is important over the largest size scales defining the cloud.

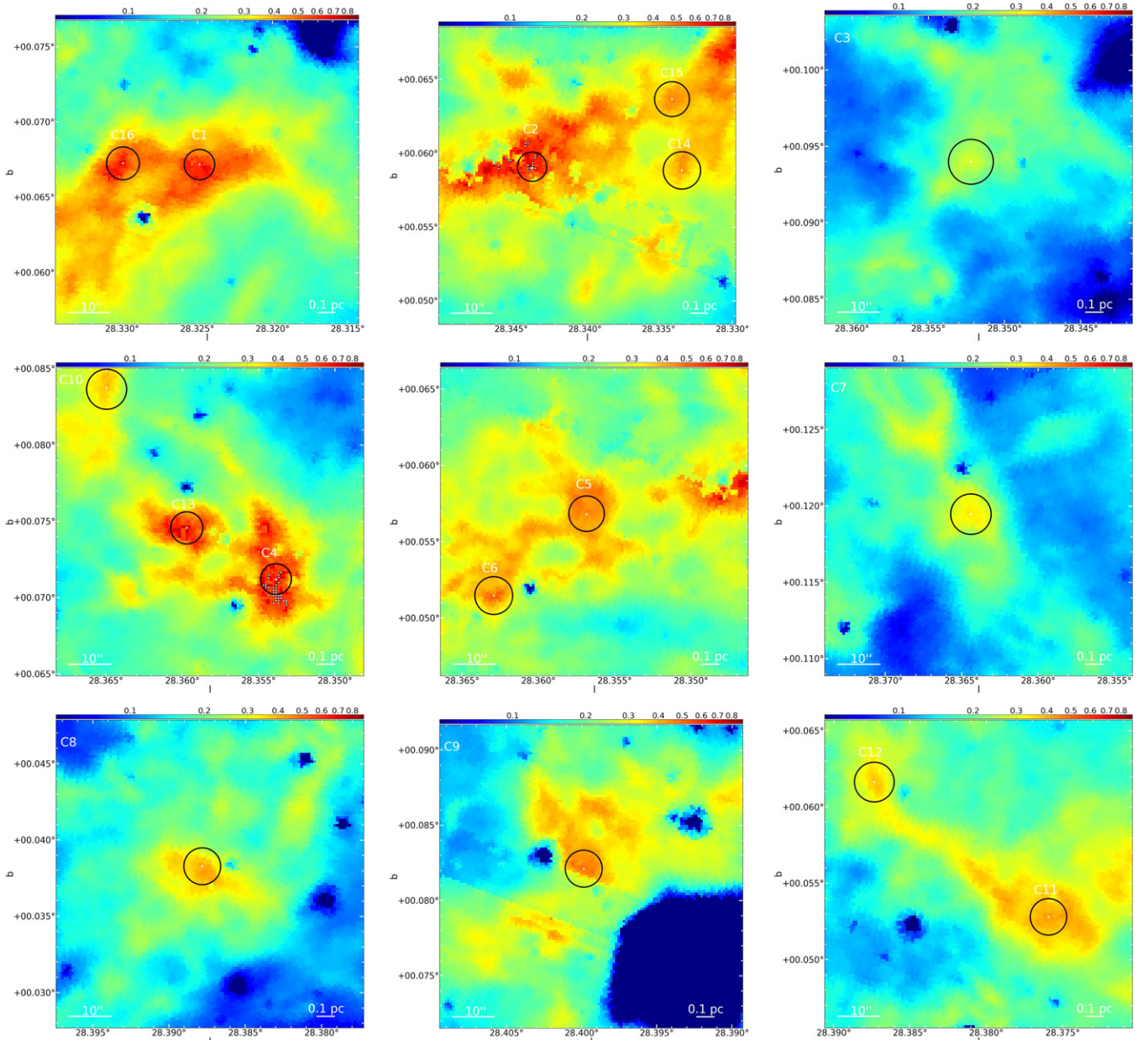
#### 3.2. Internal Structure of Cores and Clumps

The properties of nine dense core/clumps (C1–C9) within the IRDC were studied by Butler & Tan (2012). We now expand the sample, to obtain a more complete census of the massive starless or early-stage core/clumps in the cloud, identifying seven new core/clumps (C10–C16): these are the seven highest  $\Sigma$  local maxima external to C1–C9. They are also required to be free of  $8 \mu\text{m}$  sources. Zoomed-in views of the cores are presented in Figure 2.

Only C2 and C4 exhibit saturation as defined in Section 2. Following Butler & Tan (2012), we use the unsaturated portions of the  $\Sigma$  profiles to derive the power law volume density structure of the core/clumps,  $\rho_{\text{cl}}(r) = \rho_{\text{s,cl}}(r/R_{\text{cl}})^{-k_{\rho,\text{cl}}}$ , where  $\rho_{\text{s,cl}} = \mu_{\text{H}} n_{\text{H,s,cl}}$  (with  $\mu_{\text{H}} = 2.34 \times 10^{-24} \text{ g}$ ) is the density at the surface of the core/clump,  $R_{\text{cl}}$ . We hereafter refer to these objects as “clumps.” We also consider background-subtracted  $\Sigma$  profiles, where a uniform average background is evaluated from the annulus from  $R_{\text{cl}}$  to  $2R_{\text{cl}}$ , and describe these objects as “cores.”

We first consider the properties of the core/clumps at a scale that encloses  $M_{\text{cl}} = 60 M_\odot$ , which is approximately the mass scale needed to form a massive (O) star (McKee & Tan 2003). We find the mean/median/dispersion of the  $k_{\rho,\text{cl}}$  values are  $0.826/0.775/0.262$ . Equivalently, for the envelope-subtracted cores we find  $k_{\rho,c}$  mean/median/dispersion values of  $1.33/1.39/0.299$ . These are similar to the Butler & Tan (2012) results. The mean core mass is  $M_c = 14.9 M_\odot$ , so the method of envelope subtraction typically removes about 3/4 of the total mass that is projected along the line of sight. Envelope subtraction depends on the assumed three-dimensional geometry of the core and its surrounding clump and so is quite uncertain. Astrochemical tracers of starless cores, such as  $\text{N}_2\text{D}^+$ , are thus useful for helping to locate these objects more precisely (Tan et al. 2013).

The mean/median/dispersion values for  $\Sigma$  of the  $60 M_\odot$  clumps are  $0.446/0.424/0.109 \text{ g cm}^{-2}$  and for the cores are  $0.118/0.107/0.0938 \text{ g cm}^{-2}$ . If core properties are better estimated after envelope subtraction, then their  $\Sigma$ ’s are relatively small, e.g., compared to fiducial values of the turbulent core model of massive star formation (McKee & Tan 2003) with  $\Sigma \sim 1 \text{ g cm}^{-2}$  or the hypothesized minimum  $\Sigma$  threshold for massive star formation of  $1 \text{ g cm}^{-2}$  due to accretion powered



**Figure 2.** Zoom images of nine regions from Figure 1(b), illustrating 16 identified core/clumps. Top row, left to right: (a) C1, C16; (b) C2, C14, C15; (c) C3. Middle row, left to right: (d) C4, C10, C13; (e) C5, C6; (f) C7. Bottom row, left to right: (g) C8; (h) C9; (i) C11, C12. For each core/clump, the black circle shows the region enclosing  $60 M_{\odot}$ . White squares mark saturated pixels, present in C2 and C4 (see text).

(A color version of this figure is available in the online journal.)

heating suppression of fragmentation (Krumholz & McKee 2008). Even if the maximum values, i.e., with no envelope subtraction, are assigned to the cores, then these are still somewhat smaller than  $1 \text{ g cm}^{-2}$ . Note that these 16 cores are amongst the highest  $\Sigma$  peaks in the extinction map. Note also that at least some (e.g., C1) and probably most of the cores are very cold ( $\sim 10\text{--}15 \text{ K}$ ; Wang et al. 2008; Tan et al. 2013), so radiative heating is not currently suppressing their fragmentation. Magnetic suppression of fragmentation of these core/clumps, requiring  $\sim 0.1\text{--}1 \text{ mG}$  fields, remains a possibility (Butler & Tan 2012; Tan et al. 2013).

The structural properties of the core/clumps at the  $M_{\text{cl}} = 60 M_{\odot}$  scale are summarized in Table 1. Also shown here are the results of a more general fitting of power-law density profiles where the outer radius is varied and the reduced  $\chi^2$  of the fit minimized (Butler & Tan 2012). Sometimes the best-fit model is

quite close to the  $M_{\text{cl}} = 60 M_{\odot}$  model, but in other cases it can shrink somewhat or grow up to  $\sim 10^3 M_{\odot}$ . The roughly similar structural properties over a range of length and mass scales may indicate that there is a self-similar hierarchy of structure present in the IRDC. At the same time we caution that the “best-fit” model is often not that much better than models fit to other scales. Nonspherical geometries can also be important, which can limit the applicability of these simple spherical models.

### 3.3. The Mass Surface Density Probability Distribution Function

The  $\Sigma$  (or  $A_V$  or  $N_H$ ) probability distribution function (PDF), either area ( $p_A(\Sigma)$ ) or mass-weighted ( $p_M(\Sigma)$ ), entrains information about cloud self-gravity, turbulence, shocks, and

**Table 1**  
Structural Properties of Core/Clumps<sup>a</sup>

Name	$l$ ( $^{\circ}$ )	$b$ ( $^{\circ}$ )	$R_{\text{cl}} = R_c$ (pc)	$\bar{\Sigma}_{\text{cl}}$ ( $\text{g cm}^{-2}$ )	$\bar{\Sigma}_c$ ( $\text{g cm}^{-2}$ )	$k_{p,\text{cl}}$	$k_{p,c}$	$n_{\text{H},\text{s,cl}}$ ( $10^5 \text{ cm}^{-3}$ )	$n_{\text{H},\text{s,c}}$ ( $10^5 \text{ cm}^{-3}$ )	$M_{\text{cl}}$ ( $M_{\odot}$ )	$M_c^b$ ( $M_{\odot}$ )
C1	28.32450	0.06655	0.0806 0.0581	0.613 0.637	0.141 0.151	1.06 1.06	1.53 1.58	5.84 5.38	0.951 1.27	60.0 32.4	13.7 7.70
C2	28.34383	0.06017	0.0793 0.0872	0.633 0.630	0.254 0.246	1.18 1.14	1.86 1.50	6.18 3.75	2.13 1.46	60.0 72.2	24.1 28.2
C3	28.35217	0.09450	0.120 0.0581	0.276 0.287	0.0200 0.0257	0.775 0.740	1.18 1.36	1.51 2.80	0.0822 0.251	60.0 14.6	4.36 1.31
C4	28.35417	0.07067	0.0806 0.101	0.614 0.607	0.335 0.274	1.36 1.36	1.95 1.82	6.04 2.43	2.67 1.10	60.0 94.6	32.7 42.8
C5	28.35617	0.05650	0.0942 0.0872	0.449 0.453	0.0575 0.0670	0.538 0.5200	0.979 0.600	3.73 4.31	0.371 0.637	60.0 51.8	7.67 7.70
C6	28.36267	0.05150	0.100 0.843	0.392 0.315	0.179 0.0951	0.777 0.800	1.42 1.14	3.28 0.240	1.28 0.0725	60.0 3370	27.4 1020
C7	28.36433	0.11950	0.108 0.0581	0.338 0.356	0.0494 0.0558	0.759 0.680	1.08 1.14	2.26 3.94	0.247 0.616	60.0 18.1	8.75 2.84
C8	28.38783	0.03817	0.0979 0.218	0.415 0.368	0.226 0.143	1.10 1.02	1.57 1.70	2.87 0.759	1.21 0.296	60.0 263	32.6 103
C9	28.39950	0.08217	0.0997 0.0872	0.401 0.405	0.0496 0.0553	0.707 0.740	1.14 1.14	3.64 2.98	0.331 0.408	60.0 46.3	7.43 6.34
C10	28.36486	0.08397	0.107 0.0872	0.346 0.351	0.0456 0.0508	0.737 0.480	1.23 1.12	2.66 2.61	0.235 0.378	60.0 40.2	7.90 5.82
C11	28.37600	0.05279	0.0968 0.130	0.424 0.421	0.107 0.100	0.563 0.520	0.920 0.980	3.47 2.24	0.729 0.536	60.0 108.	15.1 25.9
C12	28.38717	0.06128	0.106 0.0581	0.352 0.370	0.0450 0.0564	0.900 0.860	1.42 1.64	2.62 2.99	0.279 0.455	60.0 18.8	7.66 2.87
C13	28.33317	0.05900	0.0846 0.0872	0.557 0.555	0.180 0.198	1.04 1.00	1.47 1.56	5.2 3.17	1.40 1.13	60.0 63.6	19.4 22.7
C14	28.33401	0.06383	0.103 0.130	0.374 0.372	0.0408 0.0445	0.383 0.360	1.07 0.720	2.87 2.24	0.261 0.268	60.0 95.9	6.54 11.4
C15	28.33418	0.06366	0.0956 0.290	0.435 0.409	0.136 0.0994	0.621 0.160	1.39 1.00	3.60 0.974	0.938 0.236	60.0 521	18.7 126
C16	28.32985	0.06717	0.0878 0.0581	0.516 0.521	0.0350 0.0344	0.710 0.620	1.09 1.10	4.65 5.88	0.263 0.389	60.0 26.5	4.07 1.75
Mean			0.0963 0.152	0.446 0.441	0.118 0.106	0.826 0.754	1.33 1.26	3.78 2.92	0.836 0.594	60.0 302	14.9 88.5
Median			0.0979 0.0872	0.424 0.409	0.107 0.0951	0.775 0.740	1.39 1.14	3.60 2.98	0.729 0.455	60.0 63.6	13.7 11.4
Dispersion			0.0115 0.195	0.109 0.114	0.0938 0.0763	0.262 0.313	0.299 0.353	1.41 1.54	0.750 0.417	0.00 828	9.84 251

**Notes.**

<sup>a</sup> First line for each source shows results at the scale where the total projected enclosed mass is  $M_{\text{cl}} = 60 M_{\odot}$ ; second line shows results at the “best-fit” scale, minimizing the reduced  $\chi^2$  of the projected power law density fit to the  $\Sigma(r)$  profile.

<sup>b</sup> Based on fitted power law density profile, which compensates for mass missed in saturated core centers, i.e., relevant for C2 and C4, typically  $\lesssim 10\%$  of total.

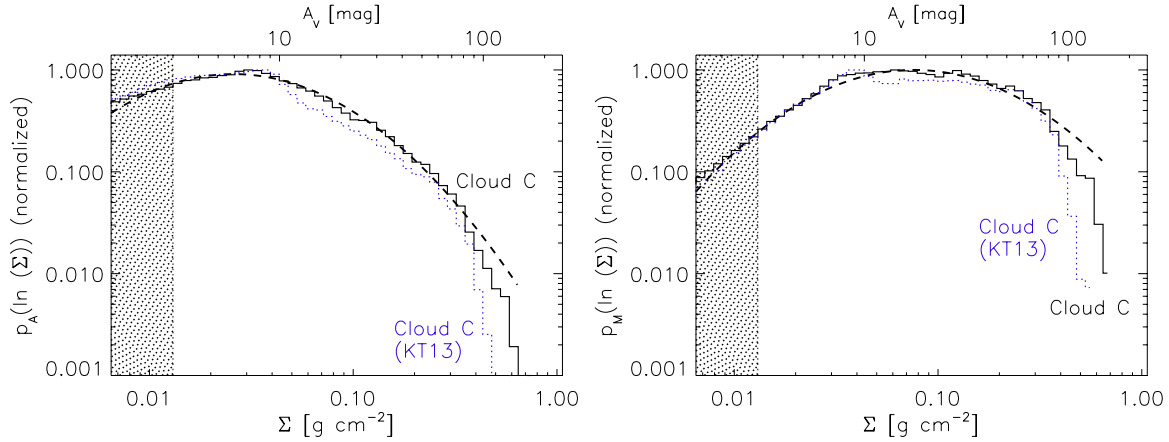
magnetic field support. Our temperature-independent high-dynamic range extinction map can yield the best constraints on the  $\Sigma$  PDF. However, the relatively limited areal coverage of the archival *Spitzer* data require us to utilize the GLIMPSE-based maps of Kainulainen & Tan (2013; offset-corrected to smoothly join the new map) to extend the region to completely cover a  $20' \times 19'$  rectangular area that encloses an  $A_V = 3$  mag contour (cf. the  $15' \times 15'$  area enclosing the  $A_V = 7$  mag contour of Kainulainen & Tan 2013).

The area- and mass-weighted  $\Sigma$  PDFs are shown in Figure 3. The new PDF extends to both lower and higher values of  $\Sigma$

compared to that derived by Kainulainen & Tan (2013). We fit a log-normal function to  $p_A(\ln \Sigma)$ , and then use this to derive  $\overline{\ln \Sigma}$  (over the considered range of  $\Sigma$ ), which then defines the mean  $\bar{\Sigma}_{\text{PDF}} \equiv e^{\overline{\ln \Sigma} + \sigma_{\ln \Sigma}^2/2}$ , where  $\sigma_{\ln \Sigma}$  is the standard deviation of  $\ln \Sigma$  (note typo in Equation (26) of Kainulainen & Tan 2013), used to define the mean-normalized mass surface density,  $\Sigma' \equiv \Sigma / \bar{\Sigma}_{\text{PDF}}$ . For this distribution, we find the best-fit log-normal

$$p_A(\ln \Sigma') = \frac{1}{(2\pi)^{1/2} \sigma_{\ln \Sigma'}} \exp \left[ -\frac{(\ln \Sigma' - \overline{\ln \Sigma})^2}{2\sigma_{\ln \Sigma'}^2} \right], \quad (1)$$





**Figure 3.** (a) Left: area-weighted probability distribution function of  $\Sigma$  for IRDC G028.37+00.07 (Cloud C; black histogram) and best-fit log-normal (dashed line) covering a contiguous region completely enclosing an  $A_V > 3$  mag contour—above this level, shown by the shaded/nonshaded boundary, the PDF is complete, modulo saturation effects for  $A_V \gtrsim 200$  mag. We also show the Kainulainen & Tan (2013)-derived PDF (purple histogram), based on a shallower, smaller dynamic range extinction map. (b) Right: mass-weighted PDFs, with same notation as (a).

(A color version of this figure is available in the online journal.)

where  $\sigma_{\ln \Sigma'}$  is the standard deviation of  $\ln \Sigma'$ . We find  $\bar{\Sigma}_{\text{PDF}} = 0.039 \text{ g cm}^{-2}$  (i.e.,  $\bar{A}_{V,\text{PDF}} = 9.0$  mag) and  $\sigma_{\ln \Sigma'} = 1.4$ , compared with the 8.3 mag and 1.7 found by Kainulainen & Tan (2013), respectively. Note that, Kainulainen & Tan (2013) only fit to  $A_V > 7$  mag, insufficient to determine the PDF peak so the parameters of their log-normal fit are less accurate.

The derived PDF is well fit by a single log-normal. Deviation at high  $\Sigma \gtrsim 0.5 \text{ g cm}^{-2}$  may be due to saturation (Section 2) or absence of MIR-bright high  $\Sigma$  regions. The value of  $\bar{A}_{V,\text{PDF}}$  is much higher than in nearby star-forming clouds ( $\bar{A}_{V,\text{PDF}} \simeq 0.6\text{--}3.0$  mag; Kainulainen et al. 2009). G028.37+00.07 also has a higher dense gas fraction than other studied IRDCs (e.g., Kainulainen & Tan 2013). The PDF shows no indication of a high-end power law tail (indeed there is no room for such a tail if the PDF peak is dominated by the log-normal), observed in some clouds (e.g., Kainulainen et al. 2011) and modeled as being due to a separate self-gravitating component (e.g., Kritsuk et al. 2011; however, see Kainulainen et al. 2011b). Since the observed linewidths (Section 3.1) indicate the overall cloud is self-gravitating, this may imply that a self-similar, self-gravitating hierarchy of structure is present over the complete range of spatial scales in the cloud probed by our extinction map and that such a hierarchy produces a log-normal-like  $\Sigma$  PDF (see also Goodman et al. 2009). This needs to be explored in global (non-periodic box) simulations of magnetized, self-gravitating molecular clouds.

We thank the referee for helpful comments. We acknowledge NASA grant ADAP10-0110 (J.C.T.) and Deutsche Forschungsgemeinschaft program 1573 (J.K.).

## REFERENCES

- Bonnell, I. A., Clarke, C. J., Bate, M. R., et al. 2001, *MNRAS*, **324**, 573  
 Bertoldi, F., & McKee, C. F. 1992, *ApJ*, **395**, 140  
 Butler, M. J., & Tan, J. C. 2009, *ApJ*, **696**, 484  
 Butler, M. J., & Tan, J. C. 2012, *ApJ*, **754**, 5  
 Carey, S. J., Clark, F. O., Egan, M. P., et al. 1998, *ApJ*, **508**, 2  
 Churchwell, E., Babler, B., Meade, M., et al. 2009, *PASP*, **121**, 213  
 Crutcher, R. M., Wandelt, B., Heiles, C., et al. 2010, *ApJ*, **725**, 466  
 Elmegreen, B. G. 2007, *ApJ*, **663**, 743  
 Ginsburg, A., Bressert, E., Bally, J., et al. 2012, *ApJL*, **758**, L29  
 Goodman, A. A., Rosolowsky, E. W., Borkin, M. A., et al. 2009, *Natur*, **457**, 63  
 Hernandez, A. K., Tan, J. C., Caselli, P., et al. 2011, *ApJ*, **738**, 11  
 Jackson, J. M., Rathborne, J. M., Shah, R. Y., et al. 2006, *ApJS*, **163**, 145  
 Kainulainen, J., Alves, J., Beuther, H., et al. 2011a, *A&A*, **536**, A48  
 Kainulainen, J., Beuther, H., Banerjee, R., et al. 2011b, *A&A*, **530**, A64  
 Kainulainen, J., Beuther, H., Henning, T., & Plume, R. 2009, *A&A*, **508**, L35  
 Kainulainen, J., & Tan, J. C. 2013, *A&A*, **549**, A53  
 Kritsuk, A. G., Norman, M. L., & Wagner, R. 2011, *ApJL*, **727**, L20  
 Krumholz, M. R., & McKee, C. F. 2008, *Natur*, **451**, 1082  
 Kunz, M. W., & Mouschovias, T. Ch. 2009, *MNRAS*, **399**, L94  
 Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, *MNRAS*, **379**, 1599  
 Longmore, S. N., Rathborne, J., Bastian, N., et al. 2012, *ApJ*, **746**, 117  
 McKee, C. F., & Ostriker, E. C. 2007, *ARA&A*, **45**, 565  
 McKee, C. F., & Tan, J. C. 2003, *ApJ*, **585**, 850  
 Padoan, P., & Nordlund, A. 2002, *ApJ*, **576**, 870  
 Peretto, N., Fuller, G. A., Plume, R., et al. 2010, *A&A*, **518**, L98  
 Rathborne, J. M., Jackson, J. M., & Simon, R. 2006, *ApJ*, **641**, 389  
 Reach, W. T., Rho, J., Tappe, A., et al. 2006, *AJ*, **131**, 1479  
 Simon, R., Rathborne, J. M., Shah, R. Y., et al. 2006, *ApJ*, **653**, 1325  
 Tan, J. C., Kong, S., Butler, M. J., et al. 2013, *ApJ*, **779**, 96  
 Tan, J. C., Krumholz, M. R., & McKee, C. F. 2006, *ApJ*, **641**, L121  
 Vázquez-Semadeni, E., Kim, J., & Ballesteros-Paredes, J. 2005, *ApJL*, **630**, L49  
 Wang, P., Li, Z.-Y., Abel, T., et al. 2010, *ApJ*, **709**, 27  
 Wang, Y., Zhang, Q., Pillai, T., et al. 2008, *ApJL*, **672**, L33  
 Zhang, Q., Wang, Y., Pillai, T., et al. 2009, *ApJ*, **696**, 268